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THE FABRICATION AND TESTING OF DEPLETED URANIUM BLANKET SLUGS FOR EBR-II

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W. R. Burt, Jr., R. D. McGowan, and C. H. Bean

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Metallurgy Division
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ABSTRACT

This report covers the production of depleted, unalloyed-uranium blanket slugs used in fabricating blanket elements for the Experimental Breeder Reactor II. Slug production included conversion of UF_4 to uranium metal, ingot casting, billet breakdown and rod rolling, beta heat treatment, machining, and inspection.

Emphasis is placed on evaluation of the beta heat treatment via thermal cycling tests and on grain-size uniformity of machined slugs via ultrasonic, through-transmission testing.

INTRODUCTION

The Experimental Breeder Reactor II (EBR-II) at the National Reactor Testing Station in Idaho, is an unmoderated, heterogeneous, sodium-cooled, fast reactor and power plant. The plant includes an integral fuel-reprocessing facility where irradiated fuel is processed, fabricated, and assembled for return to the reactor.[1] The EBR-II is primarily an engineering facility for determining the feasibility of this type of reactor for central-station power-plant applications. More detailed information on the reactor design and experimental purpose can be found in existing publications.[2]

The reactor is divided into three main zones: core, inner blanket, and outer blanket. Each zone consists of a number of right hexagonal elements (subassemblies), 5.82 cm (2.29 in.) across flats of the hexagon. The annular blanket surrounding the core is separated into two zones: the inner blanket and the outer blanket. The elements for these two zones are identical except for the lower, hexagonal, can adapters. Each element contains 19 blanket rods, each rod containing five 0.2% depleted, unalloyed-uranium slugs, 1.10 cm (0.433 in.) in diameter and 27.95 cm (11 in.) long, which form

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ABSTRACT

This report covers the production of depleted, unalloyed-uranium blanket slugs used in fabricating blanket elements for the Experimental Breeder Reactor II. Slug production included conversion of UF_4 to uranium-metal ingot casting, billet breakdown and rod rolling, beta heat treatment, machining, and inspection.

Emphasis is placed on evaluation of the beta heat treatment via thermal-cycling tests and on grain-size uniformity of unmachined slugs via ultrasonic through-transmission testing.

INTRODUCTION

The Experimental Breeder Reactor II (EBR-II) at the National Reactor Testing Station in Idaho, is an unmoderated, heterogeneous, sodium-cooled, fast-reactor and power plant. The plant includes an integral fuel-reprocessing facility where irradiated fuel is processed, fabricated, and assembled for return to the reactor.[1] The EBR-II is primarily an engineering facility for determining the feasibility of this type of reactor for central-station power-plant applications. More detailed information on the reactor design and experimental purpose can be found in existing publications.[1,2]

The reactor is divided into three main zones: core, inner blanket, and outer blanket. Each zone consists of a number of hexagonal elements (subassemblies) 5.82 cm (2.29 in.) across [illegible] in a hexagon. The annular blanket surrounding the core is [illegible] the inner blanket and the outer blanket. The elements for [illegible] are identical except for the lower, hexagonal can [illegible] contains 19 blanket rods, each rod containing [illegible] slugs, 1.10 cm (0.433 in.) in diameter [illegible] a 127-cm (55-in.) "active" blanket height. These uranium slugs are contained in a Type 304 stainless-steel jacket, with sodium filling the annulus between the slug and the jacket.

The core element contains three sections: upper blanket, core, and lower blanket. The upper and lower blanket sections are identical, each consisting of 19 blanket rods in a hexagonal can. The blanket rod contains two 0.2% depleted, unalloyed-uranium slugs, 0.80 cm (0.316 in.) in diameter and 22.85 cm (9 in.) long, which form a 45.7-cm (18-in.) blanket height. As with the inner and outer blanket rods, the slugs fit loosely into a Type 304 stainless-steel jacket, the annular gap being filled with sodium. The number of elements, blanket rods, and depleted uranium slugs necessary for a reactor loading is as follows:

			Number of Uranium Slugs	
Location	Number of Elements	Number of Blanket Rods (19 per element)	Small Diameter (2 per rod)	Large Diameter (5 per rod)
Upper blanket	47	893	1,986	-
Lower blanket	47	893	1,986	-
Inner blanket	66	1,254	-	6,270
Outer blanket	510	9,690	-	48,450
TOTAL	670	12,730	3,972	54,720

A total of 14,000 upper and lower blanket slugs and 82,000 inner and outer blanket slugs were required. The additional slugs compensated for losses in inspection and rod assembly and, more importantly, provided additional rods for replacing the upper and lower blanket sections in fuel-element recycling and for demonstrating plutonium recovery from breeding in the blanket elements.

This report covers the production of depleted-uranium ingots by the Union Carbide Corp. at Paducah, Kentucky; fabrication of the blanket slugs by the National Lead Co. at Fernald, Ohio; and inspection of the blanket slugs at Argonne National Laboratory, Argonne, Illinois. The assembly and inspection of the blanket rods are covered in a separate report.[3] The overall flowsheet for fabrication of the depleted-uranium blanket slugs is shown in Fig. 1.

Unalloyed uranium was selected for the blanket material to simplify the reprocessing cycle for blanket material. All rolled uranium rod stock received a beta heat treatment and water quench to minimize the effects of thermal cycling and irradiation during reactor operations.

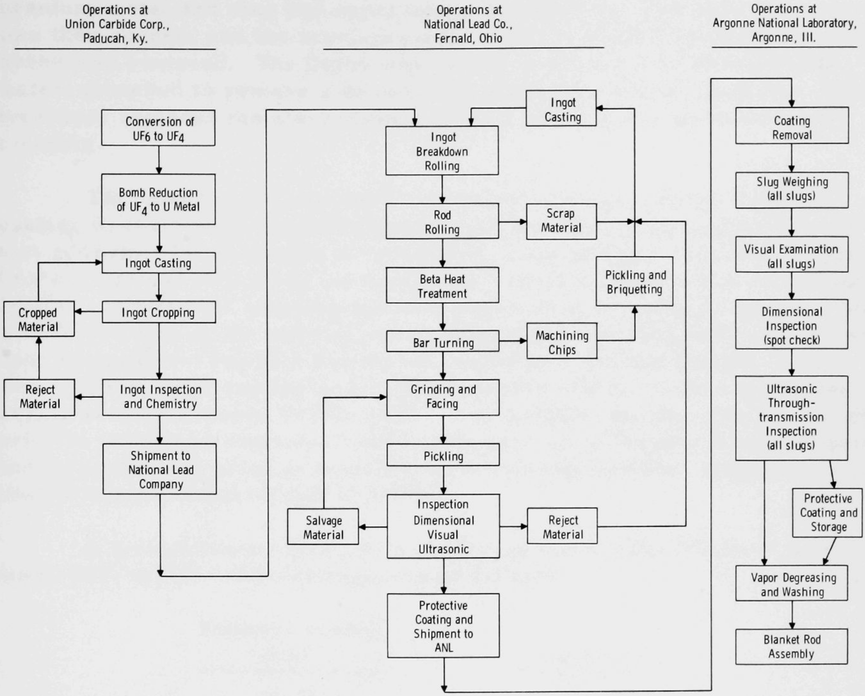

Fig. 1. Overall Flowsheet for Fabrication of Depleted Blanket Slugs

BILLET PREPARATION

Production of the depleted-uranium castings for subsequent hot rolling and blanket-slug fabrication was carried out by the Union Carbide Corp. at Paducah, Kentucky. The work included conversion of UF_6 to UF_4, reduction of UF_4 to uranium metal, and casting of 19-cm (7.5-in.)-diam, 455-kg (1000-lb) ingots with a minimum length of 61 cm (24 in.).

After conversion of gaseous UF_6 of the desired isotopic composition to the uranium tetrafluoride salt, the UF_4 was reduced to uranium metal by a magnesium-reduction operation. The thermodynamics and details of the reduction process are described in detail elsewhere.[4] Briefly, the uranium fluoride salt and magnesium powder, in an amount slightly in excess of the stoichiometric requirements, were placed in a magnesium fluoride-lined steel bomb. The bomb was placed in a heating furnace to preheat the contents to the reduction ignition temperature. After the reaction took place, the bomb was removed from the furnace and allowed to cool until the

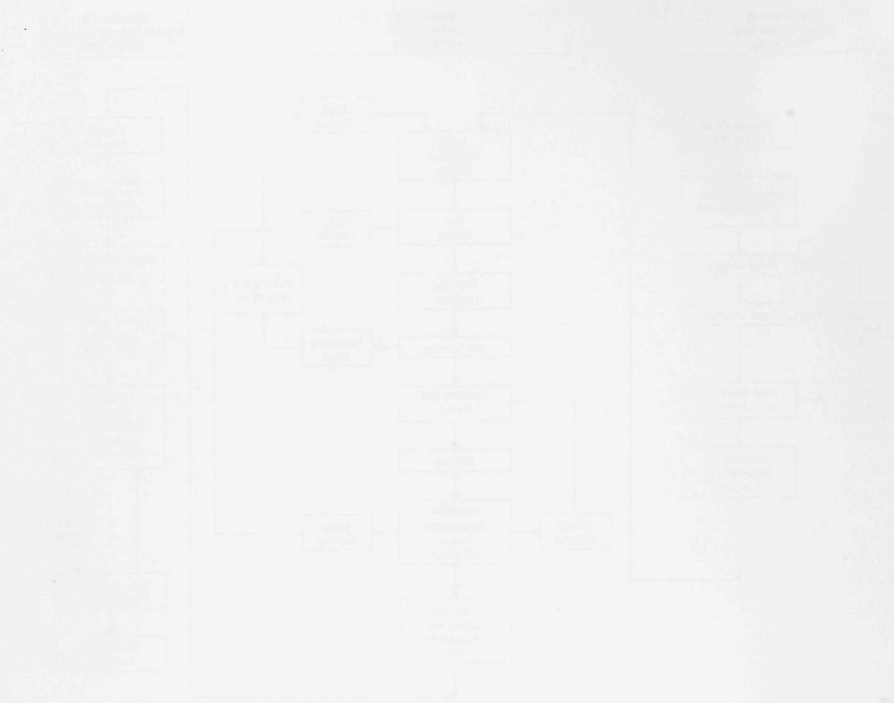

Fig. 1. Overall Flowsheet for Fabrication of Depleted Blanket Slugs

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After conversion of gaseous UF_6 [illegible] to [illegible] ammonium [illegible] salt, the [illegible] degree [illegible] reduction operation. [illegible] reduction [illegible] are described in [illegible] for [illegible] salt and magnesium powder [illegible] of the [illegible] were [illegible] was placed in a [illegible] to the reduction-ignition temperature [illegible] which was removed from the furnace [illegible] uranium metal and slag had separated and solidified. The reaction vessel was then opened, and the uranium metal in the form of a 455-kg (1000-lb) derby was removed. The derby was heated in air for 2 hr at 600°C and water-quenched to remove adherent slag and other foreign material. This technique replaces the older method of acid pickling and abrasive blast cleaning.

The uranium derbies were converted into ingots by melting and casting in steel-shell induction-heated vacuum furnaces equipped for bottom pouring. Two furnaces were utilized, each having a capacity of approximately 685 kg (1500 lb) of uranium, which could be heated to a maximum of 1550°C. Mechanical pumping systems maintained vacuums of approximately 1 to 2 Torr during the melting and casting cycle. Melting and casting were done in graphite crucibles and molds coated with mullite ($3Al_2O_3 \cdot 2SiO_2$). The coatings were applied by brushing a water slurry on the surface and drying at temperatures of 200-300°C. The graphite molds were preheated prior to casting by electrical-resistance-type strip heaters in one furnace, and by preheating prior to insertion in the second furnace. Molds were preheated to approximately 525 to 550°C.

A typical power-time cycle used in producing the 19-cm (7.5-in.) diam, 455-kg (1000-lb)-castings was as follows:

Furnace Output (kW)	Time (min)
25-40	5
50	5
75	5
100	5
175	135 (maximum)*
Power off	5--pour

*Maximum time or 1400-1425°C (optical reading), whichever occurs first.

After the castings were removed from the furnace, they were water-quenched to facilitate cooling and transferred to a cut-off station for cropping of the hot top and pipe. From 90 to 135 kg (200 to 300 lb) of hot top was removed as was all visible pipe extending down into the casting. All cropping was done with power hacksaws. The cropped castings were inspected for visual surface defects. Ingots were rejected for pipe greater than 0.32 cm (1/8 in.) in diameter and 0.64 cm (1/4 in.) in depth, pinhole porosity or surface imperfections covering an area greater than 39 sq cm (6 sq in.), or depressions such as cold shuts deeper than 0.32 cm (1/8 in.). Fins resulting from using split graphite molds were ground off. Cropped material and defective ingots were recycled through the melting and casting process.

When metal and slag had separated and solidified, the [illegible] vessel was then opened, and the vacuum cover was removed [illegible] derby was removed. The derby was treated in a [illegible] and was [illegible] to remove adhering slag and other foreign material. This technique replaces the older method of [illegible] and extensive cleaning.

The uranium derbies were converted into ingots by melting and casting in [illegible] induction heated vacuum furnaces [illegible] [illegible] furnaces were utilized, [illegible] approximately [illegible] of uranium, [illegible] [illegible] °C. [illegible] pumping [illegible] required approximately 1 to 2 Torr [illegible] the melting and [illegible] and casting were done in [illegible] crucibles and [illegible] (ZrO_2). The coatings were applied by [illegible] and drying at temperatures of [illegible]. The [illegible] were preheated prior to [illegible] by electrical resistance [illegible] furnace, and by [illegible] prior to [illegible] the second [illegible] were preheated [illegible] approximately [illegible] °C.

A typical power [illegible] cycle used in producing the [illegible] (7.5-in.) diameter [illegible] kg (1000-lb) [illegible] was as follows:

Time (min)	Furnace Output
5	[illegible]
5	[illegible]
5	[illegible]
5	[illegible]
135 (maximum)*	[illegible]
5 + pour	[illegible]

*Maximum time or 1400-1425°C (optical reading) whichever occurs first.

After the castings were removed from the furnace they were [illegible] quenched to facilitate cooling and transferred to a cut-off station for cropping. The hot top [illegible]. From 90 to 135 kg (200 to 300 lb) of hot top was removed as was [illegible] pipe extending down into the casting. All cropping was done with [illegible] hacksaws. The cropped castings were inspected for [illegible] surface [illegible]. Ingots were rejected for pipe greater than [illegible] (1/8 in.) [illegible] diameter and 0.64 cm ([illegible] in.) in depth, pinhole porosity or surface [illegible] covering an area greater than [illegible] (6 sq in.), or [illegible] such as [illegible] white deeper than 0.32 cm [illegible] [illegible] resulting from metal [illegible] molds were graded [illegible] material and [illegible] ingots were recycled through the melting and [illegible] process.

A total of 225 acceptable castings were produced by utilizing 106,726 kg (234,798 lb) of derby charge material and 16,775 kg (36,905 lb) of recycle material, which produced 105,704 kg (232,549 lb) of acceptable billet material. This represented a yield of 80.6% on total charge material and 99.0% on original derby material.

Specifications on ingot chemistry are shown in Table I, together with average, maximum, and minimum contents for all ingots produced. During the initial production of these castings, it was found that the carbon content of the ingots was below the desired lower limit of 200 ppm. Therefore, a total of approximately 200 g of -20 mesh carbon powder was added to the charge to insure an ingot carbon content within the specified limits. A 200- to 500-ppm level of carbon was desired to improve the hot-rolling characteristics of the metal and to promote grain-size uniformity.

TABLE I. Ingot Analyses and Specification Composition

Element	Specification	Ingot Analyses, ppm*		
		High	Low	Average
U^{235}	0.22 ± 0.02 w/o	0.2313	0.2087	0.2148
Boron	1 ppm max	1	NF	NMA
Cadmium	1 ppm max	<1	NF	NMA
Carbon	750 ppm max, preferably 200-500 ppm	740	60	308
Chromium	100 ppm max	<20	NF	NMA
Copper	100 ppm max	70	4	15
Iron + Nickel	300 ppm max	290	70	160
Magnesium	25 ppm max	10	<5	NMA
Manganese	150 ppm max	140	<2	48
Nitrogen	100 ppm max	88	<10	24
Silicon	150 ppm max	160**	15	75
All others†	400 ppm max	280	7	82

*Based on 225 ingots.
**One ingot analyzed 160 ppm. All others below 150 ppm.
†Includes Al, Be, Co, P, Pb, Sn, V, and Zn.
NF--Not found.
NMA--No meaningful average since analyses were usually given as "less than..."

BILLET BREAKDOWN AND ROD ROLLING

The 19-cm (7.5-in.)-diam, 455-kg (1000-lb) uranium billets were fabricated into finished blanket slugs by the National Lead Co. at Fernald, Ohio.

For breakdown rolling, the billets were preheated for 60 to 80 min in a carbonate salt bath (75% K_2CO_3-25% Li_2CO_3) at 625 to 650°C and broken down on a 56-cm (22-in.), two-high, Birdsboro blooming mill. A roll schedule of 19 passes was employed, and the billets finished as 3.8 x 6.4-cm (1.5 x 2.5-in.) oval bars. Each oval bar was hot-sheared into two 5.2-m (17-ft) lengths.

The oval bars were transferred to an equalizing salt-bath furnace (composition similar to the carbonate salt bath mentioned earlier) for a minimum soak of 12 min at 650°C prior to further reduction on a continuous-bar mill. The mill consisted of six Birdsboro stands in tandem. Mills 1, 3, and 5 were vertical mills with oval-edge-oval rolls; mills 2, 4, and 6 had horizontal round rolls. The oval bars were reduced to 3.8-cm (1.5-in.)-diam rounds, with nominal reductions of 15% per stand after an initial 6% reduction in the first mill. Bars entered the first mill at 27 m/min (90 ft/min) and left the No. 6 mill at 76 m/min (250 ft/min), the exit-bar temperature being approximately 590 to 620°C. The 12-m (40-ft)-long bars leaving the No. 6 mill were fed into a Birdsboro flying shear, where they were cut into 6-m (20-ft) lengths and run onto a cooling bed.

Further rolling of the bars, first to a 2.21-cm (0.875-in.) diam and then to a 1.27-cm (0.500-in.) diam, was performed in two additional passes through the continuous mill at the same preheat temperatures and rolling speeds as in the initial pass. Reductions of 17% per pass were used in these last two schedules. The finished rods were cut into approximately 6-m (20-ft) lengths. Surface quality of the 1.27-cm (0.500-in.)-diam bars was excellent. Some ovality was evident, but the bars finished within the limits of 1.27 ± 0.02 cm (0.500 ± 0.007 in.) set on the rolled diameter.

An initial shipment of 82,373 kg (181,221 lb) of ingots was rolled to 1.27-cm (0.500-in.)-diam rod. (NOTE: This represents the initial shipment of material from Paducah on which yields were measured.) From this material, approximately 27,000 m (90,000 ft) of 1.27-cm (0.500-in.)-diam bar stock weighing 71,686 kg (157,710 lb) were produced, representing an 87.0% yield. A total of 9,745 kg (21,464 lb) of solid scrap, representing 11.8% of the material, was produced and later recycled. The remaining 1.2% consisted of fines and oxide scale lost during the rolling operation. The 87% yield of acceptable 1.27-cm (0.500-in.)-diam bar stock was somewhat less

BILLET BREAKDOWN AND ROD ROLLING

The 19-cm (7.5-in.)-diam, 295-kg ([illegible] lb) [illegible] ingots were fabricated into finished [illegible] bars by [illegible], Ohio.

For breakdown rolling, the billets were preheated [illegible] in a carbonate salt bath ([illegible] K_2CO_3 [illegible]) and broken down on a [illegible]-cm (22-in.), two-high, [illegible] mill. A roll schedule of 1[illegible] passes was employed [illegible] and the [illegible] ([illegible] 2.5-in.) bars. Each [illegible] 2-m (17-ft) lengths.

The [illegible] bars were transferred to [illegible] furnace (composition similar to the [illegible] bath [illegible]) for a minimum [illegible] of 12 min at [illegible] prior to [illegible] rolling on a continuous-bar mill. The mill consisted of six [illegible] stands. Mills 1, 3, and 5 were vertical mills with [illegible]-edge-oval rolls; [illegible] and [illegible] had horizontal round rolls. The [illegible] bars were reduced to [illegible]-in.-diam rounds, with nominal reductions of 15% per stand [illegible] 8% reduction [illegible] first mill. Bars entered the first mill at [illegible] (ft/min) and left the No. 6 mill at [illegible] m/min (250 ft/min), the exit temperature being approximately 590 to [illegible]. The 12-m (40-ft)-long bars leaving the No. 6 mill were fed into a [illegible] flying shear, where they were cut into 6-m (20-ft) lengths and run onto a cooling bed.

Further rolling of the bars, first to a 2.21-cm (0.870-in.)-diam and then to a 1.27-cm (0.500-in.) diam, was performed in two additional passes through the continuous mill at the same preheat temperature and rolling speeds as in the initial pass. Reductions of [illegible]% per pass were used in these last [illegible] schedules. The finished rods were cut into approximately 6-m (20-ft) lengths. Surface quality of the 1.27-cm (0.500-in.)-diam [illegible] was excellent. Some ovality was evident, but the bars finished within the limits of 1.27 ± 0.02 cm (0.500 ± 0.007 in.) set on the rolled diameter.

An initial shipment of [illegible] kg (187,221 lb) of ingots was rolled to 1.27-cm (0.500-in.)-diam rods. (NOTE: This represents the initial shipment of material from Paducah on which yields were measured.) From this material, approximately 27,[illegible] m (90,000 ft) of 1.27-cm (0.500-in.)-diam bar stock weighing 71,[illegible] kg (1[illegible],710 lb) were produced, representing an 87.0% yield. A total of 9,[illegible] kg (21,[illegible] lb) of solid scrap, representing [illegible]% of the material, was produced and later recycled. The remaining 1.2% consisted of fines and oxide scale lost during the rolling operation. The 87% yield of acceptable 1.27-cm (0.500-in.)-diam bar stock was somewhat less than expected and was due to problems of "cobbling"* and dimensional control in the initial attempts to roll 2.21-cm (0.875-in.)-diam rods to a 1.27-cm (0.500-in.) diameter.

HOT SWAGING

Since many small-diameter [0.802-cm (0.316-in.)] blanket slugs were required, attempts were made to hot-swage 1.27-cm (0.500-in.)-diam bar stock to a smaller diameter to reduce losses on machining to the final size. Rod stock was preheated in a carbonate salt bath to 615 to 650°C and hot-swaged on a Fenn 6F machine with the aid of a power-driven feed mechanism. Feed rates were approximately 51 to 64 cm/min (20 to 25 in./min). Overall reductions of 40 to 60% were taken. While hot swaging proved feasible, adherence of the salt from the preheat bath presented difficulties in maintaining uniform rod feed and in obtaining a uniform surface finish on the as-swaged rod. A series of as-swaged rods was given a 725°C beta heat treatment in a chloride salt bath, followed by a water quench. Metallographic examination of both as-swaged and heat-treated material revealed an excessive variation in grain size. A significant number of swaged rods also exhibited centerline cracks resulting from the heavy swaging operation. Figure 2 shows (1) a typical crack indication on the ultrasonic through-transmission trace produced in nondestructive testing of a swaged rod, and (2) a photomicrograph of the actual defect.

Accordingly, hot swaging was abandoned in favor of machining the small-diameter slugs from 1.27-cm (0.500-in.)-diam bar.

BETA HEAT TREATMENT

The anisotropic characteristics of alpha-rolled uranium and subsequent dimensional instability upon irradiation or thermal cycling has been well studied and reported elsewhere.[5,6] Specifications for the EBR-II blanket slugs required a beta heat treatment and water quench to minimize preferred orientation and subsequent deleterious performance during reactor operation. Based on tests run at National Lead, the proposed production beta heat treatment for the rolled bar stock consisted of heating in a sodium chloride-potassium chloride salt bath to 735°C and holding at temperature for 5 min. The bars would then be transferred in air to a 55°C water quench, the transfer time being approximately 18 sec. To further evaluate the proposed heat treatment, production-rolled material was heat-treated at Argonne National Laboratory and evaluated by thermal cycle testing. The heat treatments consisted on heating for 5 min at 730°C, followed by three different cooling rates.

*"Cobbling" means: The failure of the bar to pass through the set of rolls in a continuous mill, with subsequent buckling and accumulation of material (between roll stands) leaving the previous stand.

then expanded and was d[illegible] of [illegible]ing** and dimensional [illegible] in the initial [illegible] to [illegible]21- [illegible]-diam rods to a [illegible] 500-[illegible]

HOT-SWAGING

[illegible] many [illegible]-diam [illegible] were [illegible] were [illegible] 1.27-cm (0.500-[illegible] bar [illegible] to [illegible] diam[illegible] on [illegible] and [illegible] preheated [illegible] salt bath to [illegible] and [illegible]swaged [illegible] of a [illegible]. [illegible] size of [illegible] Overall [illegible]. [illegible] sible, [illegible] of the [illegible] the [illegible] maintain[illegible] and in obtaining [illegible] the [illegible]. A [illegible] of [illegible]-swaged [illegible] heat [illegible] salt bath, followed by a [illegible] logical [illegible] hot-swaged and heat-treated [illegible] revealed an [illegible] alpha. A significant number of [illegible] also [illegible] resulting from the heavy [illegible] Figure [illegible] shows (1) [illegible] crack indication on the [illegible] ultrasonic [illegible] nondestructive testing of a [illegible] (2) a [illegible] of the actual defect.

[illegible] hot-swaging was abandoned in favor of machining [illegible] from 1.27-cm (0.500-in.)-diam bar.

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**"Cobbling" means [illegible] in a continuous [illegible] subsequ[illegible] terial [illegible] roll [illegible]) leav[illegible]

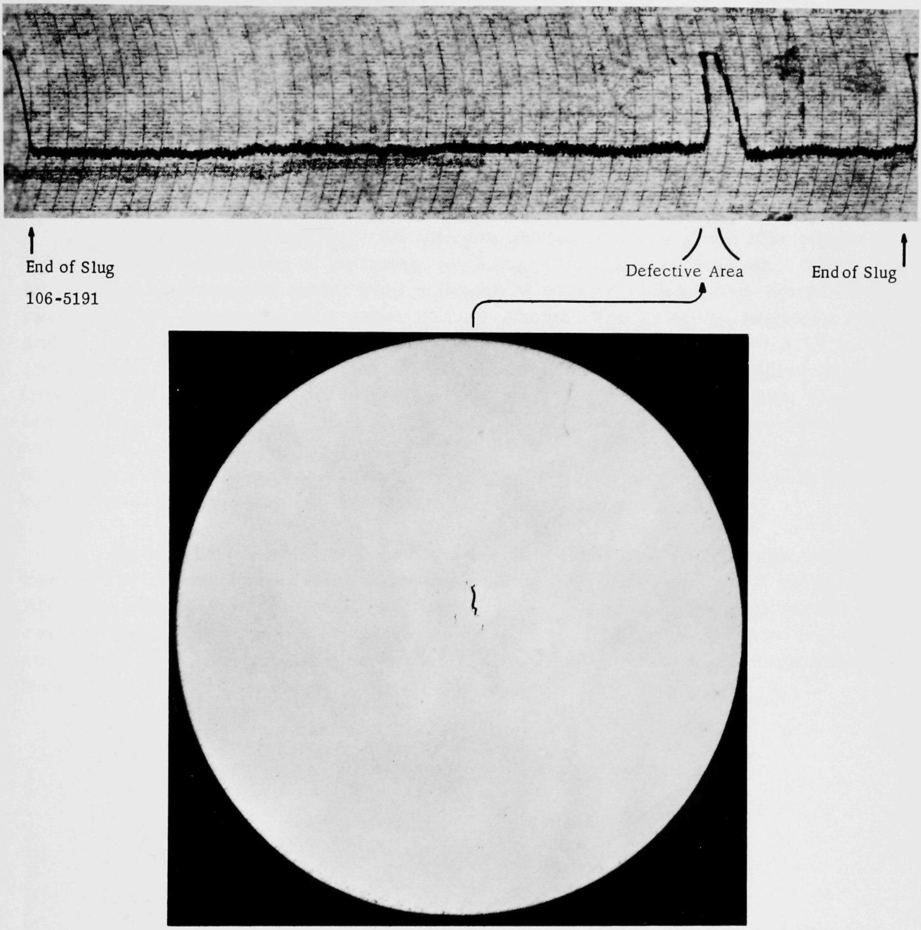

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Fig. 2. Photographs of Ultrasonic, Through-transmission Trace and Defective Area in Slug Fabricated by Hot Swaging

Samples were cooled by quenching in 55°C water after an 18-sec transfer time to simulate the production treatment, air-cooled from the beta-heat-treatment temperature, or transferred in 5 to 8 sec to a 25°C water quench to effect a more drastic quenching condition. The samples were thermally cycled between 300 and 600°C, these temperatures being the calculated values normal to the operating conditions of the reactor blanket. The thermal cycle consisted of 2 hr at 300°C, heating to 600°C in 30 min, holding at 600°C for 1 hr, and cooling to 300°C in 30 min. At preselected intervals of 50, 150, 300, and 500 thermal cycles, the samples were withdrawn from the cycling facility and dimensionally inspected.

After thermal cycling, all sample surfaces were generally rough but there was no indication of warping, necking, cracking, or flaking. After 50 cycles, all samples underwent a negative rate of elongation; the material receiving the more drastic water quench showed the greatest negative rate, and the air-cooled material showed the least negative rate. From 50 to 150 cycles, all material showed a positive rate of elongation. After approximately 150 cycles, the growth rate remained essentially constant, regardless of quench history. The growth rate of all samples tended to converge to a value less than 10^{-6} mm/mm/cycle (10 μin./in./cycle). No significant difference based on the various cooling rates was observed. On this basis, the proposed production treatment was deemed acceptable.

An initial group of finished 1.10-cm (0.433-in.)-diam slugs was processed through the heat treatment and machining operations and shipped to ANL for evaluation. Six different rods were sectioned in a longitudinal direction (parallel to the rolling direction of the rod stock), and one rod was sectioned in two separate locations. All rods exhibited minor discontinuous inclusions aligned in the rolling direction, as shown in Fig. 3.

Fig. 3
Photomicrograph Showing Typical Inclusion Content of Finished Blanket Slugs

25817 75X

The grain size appeared uniform in all samples and in the two samples from the same rod. On a line-intercept method, the average grain diameter was approximately 0.10 mm, which was within the specification size of 0.05 to 0.15 mm. Figure 4 shows the typical microstructure from three different finished slugs.

In addition to evaluating the proposed beta-heat-treatment process, a study was made to determine the stability of the beta-heat-treatment structure with the subsequent sodium-bonding heat treatment given the assembled blanket rod at ANL. To insure bonding, loaded blanket rods normally received a heat treatment of 16 hr at 450°C. Before actual determination of the production bonding cycle, it was thought that a cycle of 24 hr at 550°C might be necessary. Accordingly, beta-heat-treated production material was vacuum-annealed for 24 hr at the higher temperature of 550 to 560°C for evaluation of possible microstructural changes. Metallographic examination revealed that the material had undergone recrystallization, apparently due to stresses resulting from the water quench after the beta heat treatment. However, neither hardness nor grain-size measurements indicated any deleterious effects as a result of the heat treatment.

SLUG FABRICATION

Following a straightening operation performed on a Medart rod straightener, the beta-treated bars were bar-turned to approximately 1.15-cm (0.45-in.) diameter for material for the large-diameter slugs and to approximately 0.84 cm (0.330 in.) for material for the small-diameter slugs. Two passes through the bar-turning machine were required to produce stock for the small-diameter slugs. Following turning, the bars were rough-cut to length on an abrasive wheel, leaving approximately 0.08 cm (0.031 in.) over the finished slug length. The rough-cut slugs were centerless-ground to their final diameters in two or three heavy passes, with a final light pass for a good surface finish. While specifications called for a 2.5-micron (100-μin.) finish, actual finishes were approximately 1.6 microns (64 μin.). The good surface finish was required to promote sodium wetting and to facilitate visual inspection for surface defects. The final diameters were held to within ±0.0012 cm (±0.0005 in.). Slug ends were faced to within ±0.012 cm (±0.005 in.) of the nominal final length, and the ends were deburred. The machined slugs were degreased, given a light pickle in cold HNO_3 and a hot-water rinse, and dried in hot air. The purpose of the nitric acid pickle was to facilitate detection of surface defects in subsequent visual examination.

SLUG INSPECTION AND SHIPMENT BY VENDOR

Following the pickling cycle, all slugs were given a visual surface inspection for pits, seams, laps, voids, or inclusions greater than 0.08 cm (0.031 in.) in any direction. After a dimensional inspection of length and

The grain size appeared uniform [illegible] and in the two samples from the same rod. On a [illegible], the average grain diameter was approximately [illegible] mm, [illegible] was within the specification range of 0.05 to 0.15 mm. Figure 4 shows [illegible] microstructure from three different finished slugs.

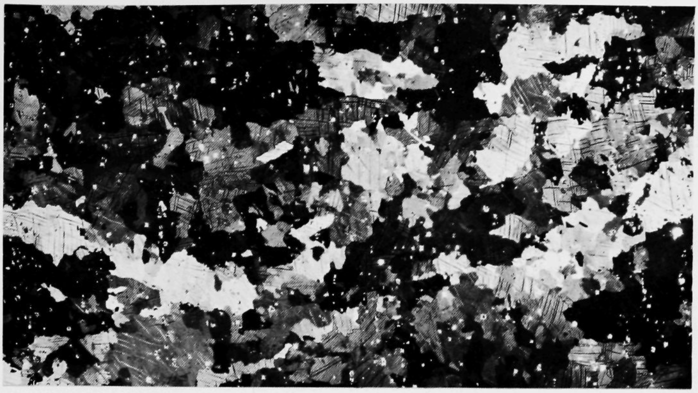
In addition to evaluating [illegible] beta-heat-treatment process, a study was [illegible] to determine the [illegible] of the beta-heat-treatment structure with the subsequent [illegible] heat treatment given the assembled blanks [illegible] at [illegible] bonding, [illegible] normally received a heat [illegible] 18 hr at 450°C. [illegible] termination of the product [illegible] cycle, it was thought that [illegible] 24 hr at 550°C might be necessary. [illegible] beta-heat-treated [illegible] material [illegible] vacuum [illegible] for 24 hr at the higher temperature of 550 to 560°C and examined [illegible] microstructural changes. [illegible] graphic examination [illegible] underwent [illegible] zation, apparently due to [illegible] resulting from the water quench of the beta heat treatment. However, neither hardness nor grain-size measurements indicated any [illegible] effects as a result of the heat treatment.

SLUG FABRICATION

Following a straightening operation performed on a Medart rod straightener, the beta-treated bars were bar-turned to approximately 1.15-cm (0.455-in.) diameter for material for the large-diameter slugs and to approximately 0.84 cm (0.330 in.) for material for the small-diameter slugs. [illegible] passes [illegible] bar-turning machine were required to produce size for the small-diameter slugs. Following turning, the bars were rough-cut to [illegible] on an abrasive wheel, leaving approximately 0.08 cm (0.031 in.) over the [illegible] length. The rough-cut slugs were centerless-ground to [illegible] diameters in [illegible] heavy passes, with a final light pass [illegible] good surface finish. While specifications called for a 2.5-micron (100-[illegible]) finish, actual finishes were approximately 1.6 microns (64 μin.). The good surface finish was required to promote sodium wetting and to facilitate visual inspection for surface defects. The final diameters were [illegible] within ±0.0012 cm ([illegible] 005 in.). Slug ends were faced [illegible] cm (±0.005 in.) of the nominal final length, and the ends were deburred. The machined slugs were [illegible] given a light pickle in cold HNO_3, and a hot-water [illegible] nitric acid [illegible] to facilitate [illegible] surface [illegible] visual examination.

SLUG INSPECTION [illegible]

Following the [illegible] cycle, all slugs were given a visual surface inspection for pits, seams, laps, voids, or inclusions greater than 0.08 cm (0.031 in.) in any direction. [illegible] dimensional inspection of length and



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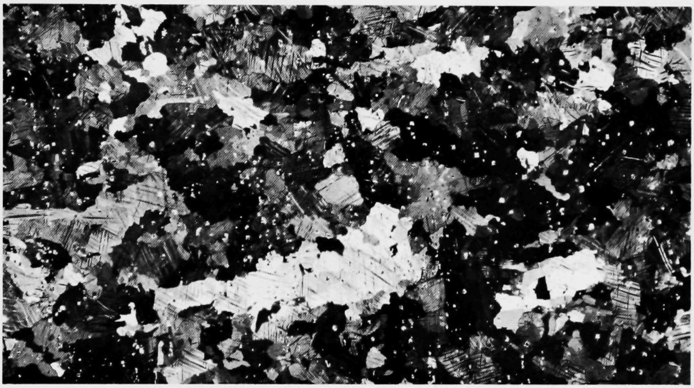

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Fig. 4. Typical Microstructures from Three Different Finished Slugs

diameter and an inspection for straightness, the slugs were given an ultrasonic velocity test for detection of untransformed alpha phase present in material that had not received the proper beta heat treatment. The ultrasonic test was made with the probes immersed in a tank of Shell Oil Company No. 210 Ensis oil, a paraffin-base derivative. The oil provided an adequate transmission medium for the test and protected the slugs from surface pitting, which occurred if uncoated slugs were left sitting in open air for a day or two. After the test, the slugs were supported vertically to allow the excess oil to drain off and leave a semisolid, adherent, protective coating on the slug.

The coated slugs were packed vertically in wooden boxes lined with aluminum foil for shipment to Argonne National Laboratory.

The following is a tabulation of inspection results at National Lead on small-diameter, upper and lower blanket slugs:

Slugs received from machining operations	
New stock	20,530
Recycle stock	470
Total	21,000
Acceptable slugs shipped to ANL	16,050
Scrap slugs	4,470
Slugs for laboratory evaluation	10
Slugs recycled	470

The acceptable slugs represent a 78.2% yield from the 20,530 machined slugs. The 16,050 slugs represent approximately 11,350 kg (25,000 lb) of 1.2-cm (0.500-in.)-diam bar stock. Of the reject material, the dimensional inspection accounted for approximately two-thirds of the rejects; visual rejects (seams, pits, nicks, machining marks, or other surface defects larger than 0.08 cm in any direction) accounted for the balance.

No detailed records were kept on inspection of large-diameter slugs, but the yield of good slugs was equal to, or slightly better than, that obtained on the small-diameter slugs. Again, dimensional variations accounted for the majority of the rejected slugs. Slugs that were oversize in diameter or length were recycled through the grinding or facing operation to bring the slugs to within specified tolerances.

MATERIAL RECLAMATION

To increase the material yield of acceptable slugs from the initial ingots, machining chips, rejected slugs from inspection, and other scrap uranium metal were reclaimed. Chips from machining were pickled in acid to remove surface oxide and briquetted into compacts suitable for diameter and an inspection for straightness, the slugs were given an ultrasonic velocity test for detection of untransformed alpha phase present in material that had not received the proper beta heat treatment. The ultrasonic test was made with the slugs immersed in a tank of Shell Oil Company No. 210 [illegible] oil, a [illegible]-base derivative. The oil provided an adequate [illegible] medium for the test and protected the slugs from surface pitting [illegible] it uncoated slugs were left sitting in open air for a day or [illegible] after the test, the slugs were supported vertically to allow the excess [illegible] to drain off and leave a [illegible], coherent, protective coating on [illegible].

The [illegible] slugs were packed [illegible] wooden boxes lined with aluminum [illegible] for shipment to Argonne National Laboratory.

The following is a tabulation of inspection results at National Lead on small-diameter, upper and [illegible] slugs:

[illegible] received from [illegible] operations
[illegible] stock
[illegible] stock [illegible] 470
[illegible] Total

[illegible] slugs shipped [illegible]
[illegible] slugs
[illegible] laboratory [illegible]
[illegible] samples

[illegible] acceptable slugs [illegible] from the 20,550 machined [illegible]. The 16,050 slugs [illegible] approximately 11,450 kg (25,000 lb) of 1.2-cm [illegible] [illegible]. [illegible] the dimensional inspection accounted for approximately [illegible]; visual rejects [illegible] nicks, machining [illegible] surface defects larger than 0.0[illegible] [illegible] detection [illegible].

No [illegible] were [illegible] large-diameter slugs, but the yield [illegible] slugs was [illegible] than that obtained on the small-diameter slugs. [illegible] accounted for the majority [illegible] rejected [illegible] slugs that were oversize in diameter or length were [illegible] through the grinding or facing operation to bring the slugs to within specified tolerances.

MATERIAL RECLAMATION

[illegible] the material yield of acceptable slugs from the initial ingots, machining chips, rejected slugs from inspection, and other scrap uranium metal were reclaimed. Chips from machining were pickled in acid to remove surface oxide and briquetted into compacts suitable for charging to a remelt operation. These briquets, together with blanket slugs and other metal, were charged into graphite crucibles, vacuum-induction melted, and cast into graphite molds in a manner similar to that described for the initial ingots produced by the Union Carbide Corp. All reclamation was done at the facilities of the National Lead Company. An additional 40 ingots were realized through this reclamation process, including eight ingots that were slightly out of specification as to minor elements but were accepted by Argonne National Laboratory.

These ingots resulting from reclamation were processed in a manner similar to that described earlier for the original ingots.

SLUG INSPECTION AT ANL

Prior to assembly into blanket tubes, all uranium slugs received the following inspections:

(1) Visual examination of the surface for pits, laps, seams, cracks, or other defects greater than 0.08 cm (0.031 in.) in any direction.

(2) Weight checks to assure an acceptable density.

(3) Ultrasonic through-transmission testing for detecting internal defects such as cracks, for assuring proper beta heat treatment, and for determining adequacy and uniformity of the grain size.

(4) A dimensional and straightness recheck on every 24th slug.

To meet the specification of a minimum density of 18.7 g/cc for blanket slugs, a group of 60 slugs was taken from small-diameter slugs and a similar group from large-diameter slugs. The two groups were measured by an immersion technique for density and volume. The resulting data are shown in Table II. The average density was 18.96 g/cc.

TABLE II. Density, Volumetric, and Weight Measurements on Blanket Slugs

Measurement	Blanket Slug Size	
	1.10-cm (0.433-in.)-diam, Group of 60 Slugs	0.80-cm (0.316-in.)-diam, Group of 60 Slugs
Density		
Average	18.96 g/cc	18.96 g/cc
Range	18.89 to 19.03 g/cc	18.89 to 19.02 g/cc
Volume		
Average	26.542 cc	11.543 cc
Range	25.484 to 26.604 cc	11.508 to 11.570 cc
Variance (S^2)	0.000668	0.000192
Standard Deviation (S)	0.0259	0.0138
Weight		
Average	503.34 g	218.89 g

charging to a remelt operation. These [illegible] ings and other metal, were charged [illegible] graphite [illegible] melted, and cast into graphite molds in a [illegible] described for the initial ingots produced by the [illegible]. All reclamation was done at the facilities of the National [illegible] 40 ingots were realized through this [illegible] eight ingots that were slightly out of [illegible] but were accepted by Argonne National Laboratory.

These ingots resulting from [illegible] were processed in a manner similar to that described earlier for the original ingots.

SLUG INSPECTION AND [illegible]

Prior to assembly into blanket [illegible] slugs received the following inspections:

(1) Visual examination of the surface for [illegible], cracks, or other defects greater than 0.08 cm [illegible] in any direction.

(2) Weight checks to assure an acceptable density.

(3) Ultrasonic through-transmission testing for detecting internal defects such as cracks, for assuring proper [illegible], and for determining adequacy and uniformity of the [illegible].

(4) A dimensional and straightness check on every 24th slug.

To meet the specification of a minimum density [illegible] blanket slugs, a group of 60 slugs was taken from [illegible] and a similar group from large-diameter slugs. [illegible] measured by an immersion technique for [illegible]. The resulting data are shown in Table II. The average [illegible]

TABLE II. Density, Volume, and Weight Measurements

Blanket Slug Size		Measurement
0.83-cm (0.415-in.)-diam. Group of 60 slugs	1.10-cm (0.433-in.)-diam. Group of 60 slugs	
		Density
[illegible] g/cc	18.96 g/cc	Average
[illegible] to 19.0[illegible] g/cc	[illegible] to 19.01 g/cc	Range
		Volume
[illegible] cc	[illegible] cc	Average
11.508 to 11.570 cc	[illegible] to 26.[illegible] cc	Range
0.000152	[illegible]	Variance
[illegible]	[illegible]	Standard Deviation
		Weight
		Average

The tolerances on slug diameters being ±0.0013 cm (±0.0005 in.) and on slug lengths being ±0.013 cm (±0.005 in.), and the average measured density being significantly greater than the minimum specified density, it was possible to calculate a minimum slug weight that would insure that all slugs within specified dimensions were above the required minimum density of 18.7 g/cc. All finished slugs were weighed; those whose weight fell below the calculated minimum weight received an actual density measurement.

The purpose of the ultrasonic through-transmission test was threefold:

(1) To discover any internal defects, such as cracks, pits, etc., larger than 0.08 cm (0.031 in.) in any direction.

(2) To insure that the structure consisted of beta-treated material.

(3) To indicate areas of relatively large grain size in beta-treated material.

A permanent 1:1 trace from a strip-chart recorder was obtained on each slug. The uranium slugs were rotated and fed between the transducer heads at a speed of 61 cm/min (2 ft/min) by skewed rolls. Figure 5 shows the overall ultrasonic test equipment and recorder.

106-4978

Fig. 5. Overall View of the Ultrasonic, Through-transmission, Test Equipment Used for Inspection of Blanket Slugs

The tolerances on slug [illegible] were [illegible] and on slug [illegible] the [illegible] surface [illegible] being [illegible] greater than [illegible] possible [illegible] minimum [illegible] that [illegible] all slugs within [illegible] capacity of 18.7 [illegible] slugs [illegible] fall below the [illegible] minimum [illegible] specified [illegible] requirement.

[illegible] through [illegible] this slide [illegible]

(i) To disco[illegible] defects [illegible] pits, etc., larger than [illegible] 0.015 in. [illegible]

(ii) To [illegible] the [illegible] limited materials.

(iii) To ind[illegible] of relatively large [illegible] in the material.

[illegible] (form [illegible] the [illegible] slugs were [illegible] and [illegible] the [illegible] speed [illegible] (2.[illegible] rate 3 shows [illegible] with [illegible] equipment.

[illegible]

The typical microstructure of beta-treated material is shown in Fig. 4., where microstructures from three different rods show a similar grain size. Figure 6 shows the microstructure and ultrasonic trace from a rod rejected because of an abnormally large grain size over three-fourths

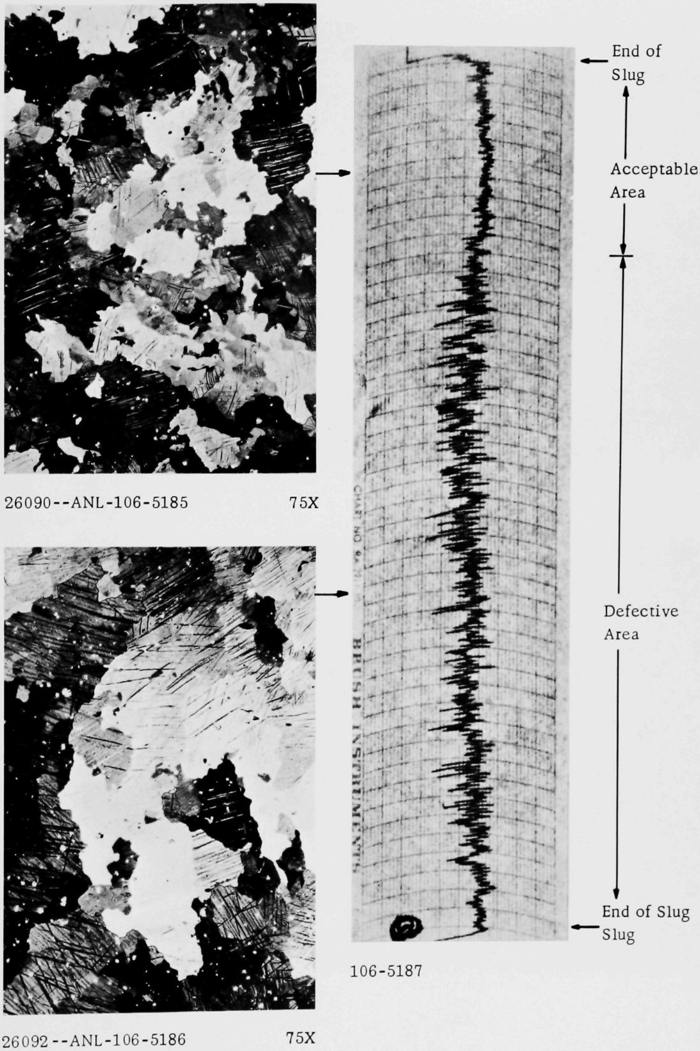
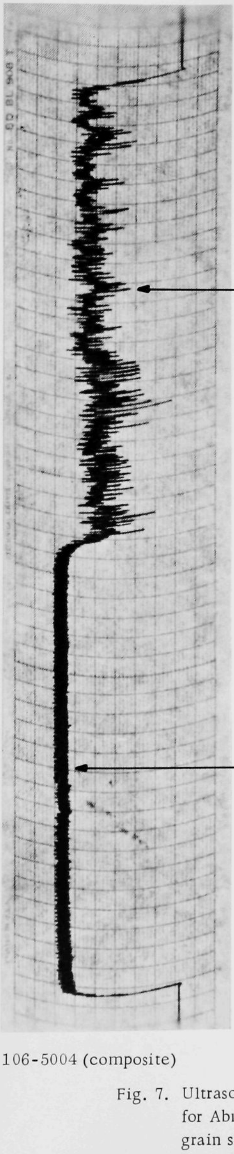
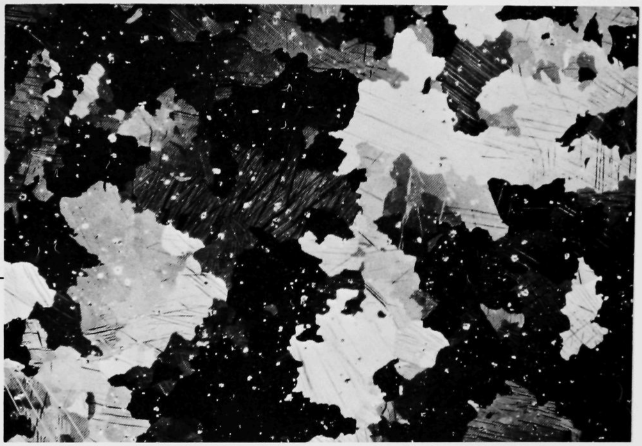


Fig. 6. Photograph of Ultrasonic, Through-transmission Trace and Photomicrographs of Corresponding Areas in EBR-II Small-diameter Production Blanket Slug. Large grain size typical of trace areas showing large oscillations.

of its length. The large grain size results in wide fluctuations on the ultrasonic transmission test trace. Figure 7 shows a rod that has a very large grain size for approximately half the rod length where the material received a beta treatment, while the other half of the rod shows a very





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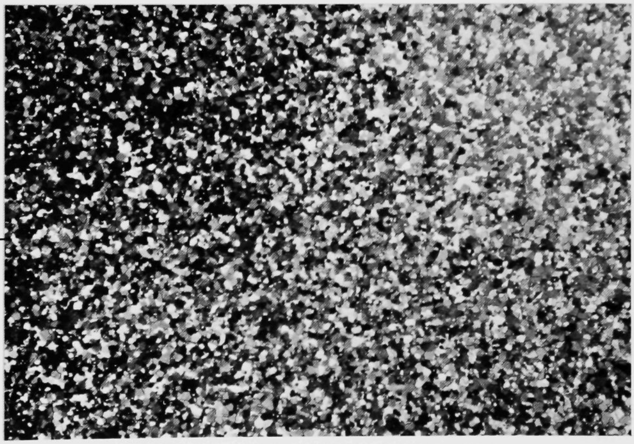

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106-5004 (composite)

Fig. 7. Ultrasonic, Through-transmission Trace of Small-diameter Slug, Rejected for Abnormally Large Grain Size. Photomicrographs show area of large grain size and also an area of alpha-recrystallized material.

fine-grained alpha-recrystallized structure. The effect of these structures on the ultrasonic trace is quite evident. X-ray diffraction studies on this rod showed a high degree of preferred orientation in the fine-grained area indicative of an as-rolled alpha structure, while the coarse-grained section exhibited considerably more random orientation, typical of beta-treated material. The effects shown on the ultrasonic trace due to large grain size (a wide fluctuation in trace width) and the presence of an as-rolled alpha structure (a displaced and very uniform trace) made it easy to distinguish material that had not received the proper beta heat treatment or material that possessed an abnormally large grain size. The as-rolled alpha structure occurred in sections of rolled rod stock that were not completely submerged in the salt bath during the beta heat treatment.

A total of 16,050 small-diameter slugs were received from National Lead; 16,047 were inspected and three were used for evaluation purposes before testing. Considering overall inspection results, 13,895 (86.6%) of the slugs inspected were acceptable, 1,827 (11.4%) were rejected for surface pitting or machining marks, and 325 (2.0%) were rejected for defects found in ultrasonic testing. Initially, the visual rejects were not tested by ultrasonics. Later, 1,309 of these visual-reject slugs were ultrasonically tested, and 1,229 (94.0%) were acceptable. Of the 15,529 slugs receiving the ultrasonic test, 405 (2.6%) were rejected. The primary reason for rejection in ultrasonic testing was abnormal grain size.

Of the 95,593 large-diameter inner and outer blanket slugs received, 94,676 slugs were inspected; 80,742 (85.3%) were approved for blanket loading, 10,776 (11.4%) were rejected in the ultrasonic test, and 3,158 (3.3%) were rejected in the visual examination. The visual-reject group was eventually sonic-tested, and 2,765 (87.6%) were acceptable, 393 (12.4%) also being sonic rejects.

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The authors wish to thank J. F. Schumar and R. E. Macherey for their overall guidance of the work, W. N. Beck for the thermal cycling data, and R. H. Selner for establishing the ultrasonic testing conditions. The personnel of the Foundry and Fabrication Group deserve thanks for their efforts in final inspection of the slugs.

Special thanks go to C. W. Loveland and the personnel at Union Carbide Corp. for the production of the ingots, and to C. E. Bussert and many others at the National Lead Company of Ohio for the production of the finished slugs. Both phases were done well and with excellent cooperation.

fine-grained alpha or Widmanstätten structure. The effect of these structures on the ultrasonic trace is quite evident. X-ray diffraction studies on this rod showed a high degree of preferred orientation in the fine-grained area indicating an as-rolled alpha structure, while the coarse-grained section exhibited considerably more random orientation, typical of beta-treated material. The effects shown on the ultrasonic trace due to changes in grain size (a random orientation in the beta-treated and the presence of an as-rolled alpha structure is displayed on the Widmanstätten trace) made it easy to distinguish material that did not receive the proper beta heat treatment or material that possessed an abnormally large grain size. The as-rolled alpha structure occurred in [illegible] of rolled rod stock that were not completely submerged in the salt bath during the beta heat treatment.

A total of [illegible] small-diameter slugs [illegible] received from National Lead; 16,08[illegible] [illegible] inspected and three were used for calibration purposes before testing. [illegible] overall inspection results, 14,801 (86.9%) of the slugs inspected were acceptable, 1,8[illegible] ([illegible]%) were rejected for surface pitting or [illegible] marks, and [illegible] were rejected for defects found in ultrasonic testing. Initially, the visual rejects were not tested ultrasonically. [illegible] 1,809 of these visual rejects were ultrasonically tested, and [illegible] were acceptable. [illegible] slugs receiving the ultrasonic test, [illegible] ([illegible]%) were [illegible] reason for rejection in ultrasonic testing was [illegible].

Of the [illegible] large-diameter [illegible] slugs received, 94,676 [illegible] inspected; 80,[illegible] were [illegible] blanket loading, 10,[illegible] ([illegible]%) were rejected [illegible] ultrasonic [illegible] and [illegible] ([illegible]%) were rejected [illegible] visual examination. [illegible] eventually [illegible] sonic [illegible] and 2,465 (81.6%) were acceptable, [illegible] being sonic rejects.

ACKNOWLEDGMENTS

The authors wish to thank J. [illegible] and [illegible] for their [illegible] of the work, W. [illegible] Beck [illegible] and R. [illegible] for establishing the ultrasonic testing conditions [illegible] sonnel [illegible] and Fa[illegible] deserve thanks for their efforts in [illegible] of the slugs.

[illegible] thanks go [illegible] and the personnel of Union Carbide [illegible] the production [illegible], and to C. E. Bussert [illegible] and many others at the National Lead Company of Ohio for the production of the [illegible]. Both phases were done with excellent cooperation.

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